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Benchmarking laboratory observation uncertainty for in-pipe storm sewer discharge measurements

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SUMMARY

The uncertainty associated with discharge measurement in storm sewer systems is of fundamental importance for hydrologic/hydraulic model calibration and pollutant load estimation, although it is difficult to determine as field benchmarks are generally impractical. This study benchmarks discharge uncertainty in several commonly used sensors by laboratory flume testing with and without a woody debris model. The sensors are then installed in a field location where laboratory benchmarked uncertainty is applied to field measurements. Combined depth and velocity uncertainty from the laboratory ranged from ±0.207–0.710 in., and ±0.176–0.631 fps respectively, and when propagated and applied to discharge estimation in the field, resulted in field discharge uncertainties of between 13% and 256% of the observation. Average daily volume calculation based on these observations had uncertainties of between 58% and 99% of the estimated value, and the uncertainty bounds of storm flow volume and peak flow for nine storm events constituted between 31–84%, and 13–48% of the estimated value respectively. Subsequently, the implications of these observational uncertainties for stormwater best-management practice evaluation, hydrologic modeling, and Total Maximum Daily Load development are considered.

1. Introduction

The value of accurate discharge measurements in urban storm sewer systems was first recognized as rudimentary flood gaging stations appeared in, and upstream of urban areas in the 1970s (Owen, 1979), but has since multiplied with the inclusion of water quality management in the stormwater paradigm (Roy et al., 2008). Discharge measurements paired with constituent concentration data allows for the estimation of pollutant loads, now regulated in many urban areas by the intersection of the National Pollutant Discharge Elimination System's (NPDES), Municipal Separate Storm Sewer System (MS4) program and the Total Maximum Daily Load (TMDL) program (Sections 402 and 303 of the Clean Water Act, respectively). Stormwater managers must now show that their localities are reducing pollutant runoff to achieve limits called Waste Load Allocations (WLAs), and though discharge measurement is necessary for pollutant load estimation, explicit requirements for discharge monitoring are absent from the MS4 and TMDL programs, and the regulation of discharge as a pollutant unto itself was prohibited by the U.S. District Court of Virginia (VDOT v. USEPA, 2013).

As the current regulatory environment does not require discharge monitoring, and may even disincentivize it (Wagner, 2005), only a small proportion of approximately 7000 regulated MS4 entities (USEPA, 2014) monitor discharge. Nevertheless, there are certain localities that have developed monitoring programs either through relationships with the USGS (e.g. Hoogestraat, 2015; Jastram, 2014; Storms et al., 2015), as a department of the local or regional government (e.g. City of Austin, 2009), or as consulting contracts (e.g. Gauron, 2015).

The literature provides thorough guidance on the measurement of discharge in open channels (Turnipseed and Sauer, 2010; USBR, 2001; WMO, 2010), but MS4 permits ascribe the water quality effects of urban stormwater to the underground system's terminal pipe discharging into jurisdictional waters of the U.S. – known as an "outfall." Furthermore, the treatment prescribed for urban stormwater pollution is a combination of programmatic measures and structural controls (Aguilar and Dymond, 2015) whose hydrologic and water quality benefit is yet unknown or uncertain (Barrett, 2008; Taylor and Fletcher, 2007). Detailed guidance addressing the nuances of monitoring storm sewer discharges from MS4 outfalls and stormwater best management practices (BMPs) is needed, and in particular, there is a need for characterization of the

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uncertainty associated with in-pipe sensor discharge measurements and its effects on the use of flow data for modeling and pollutant load estimation (Harmel and Smith, 2007). The type of uncertainty associated with sensor measurements is called "measurement" or "observation" uncertainty (McMillan et al., 2012) – the focus of this paper.

The term "uncertainty" should be distinguished from the term "error", which is defined as the difference between the true value and measured value (measurand), which is not operationally helpful since true values are almost never known (Moffat, 1988). Rather, uncertainty is defined as "a parameter associated with the result of a measurement that characterizes the dispersion of values that could reasonably be attributed to the measurement (WMO, 2010)." The two components of observation uncertainty as defined in Coleman and Steele (1995), and applied to hydrologic measurements in Bertrand-Krawjewski and Muste (2008a) are (1) uncertainty due to bias, and (2) precision uncertainty (Fig. 1). While bias and precision are typically thought of as error sources, they are defined as components of uncertainty in this paper, as the true value of the measurand is not known. Bias uncertainty is the systematic difference between the mean of the observations and the benchmark value, while precision uncertainty is the random scatter of observations about the mean, conforming to some probability distribution, and generally described by a simple statistic such as the standard deviation.

As discharge benchmarks are generally not available, there are limited studies that attempt to quantify the components of discharge observation uncertainty with applications to storm sewer field measurements. McMillan et al. (2012) provide a meta-analysis of observation uncertainty for various types of hydrologic measurements, and Lee et al. (2014) apply a standardized uncertainty framework to river flow sensor observations, but neither provide specific information regarding the measurement of discharge in storm sewer pipes. McIntyre and Marshall (2008) and Rehmel (2008) partially fill this gap by comparing acoustic Doppler current profiler observations to the commonly used impeller current meter in nine storm sewer cross sections, and 43 USGS stations respectively, however no attempt was made to perform laboratory benchmarking in these studies. Maheepala et al. (2001) perform flume calibration of flow sensors that are then placed in storm sewer pipes and evaluated, but the procedure and results of laboratory work are not reported. Heiner and Vermeyen (2013) performed laboratory evaluations of nine sensors in a rectangular, circular, and trapezoidal channel, though laboratory constraints allowed comparisons at a limited number of discharge values, and the lab results were not applied to field measurements. The literature on discharge monitoring uncertainty lacks the connection between laboratory benchmarking of sensor uncertainty, application of that uncertainty in the field, and the implications of uncertainty for stormwater monitoring, modeling, analysis, and decision making.

The purpose of this study is to benchmark the uncertainty associated with discharge measurements from several common sensors for their use in storm sewer monitoring and modeling. To do this, uncertainty is determined in the laboratory under controlled conditions, and with the effects of a woody debris model. Laboratory benchmarked uncertainty is then applied to field measurements, and finally the implications of observational uncertainty for urban storm water monitoring and modeling is discussed.

2. Instrumentation

To obtain flow measurements without structural devices (e.g. weirs and flumes), electronic sensors can be used that employ a variety of technologies to measure stage and velocity in open channels and pipes. The sensors used in this study are shown in Table 1, and the technologies employed are discussed in the following sections.

2.1. Depth measurement

Sensors that employ ultrasonic (US) technology are mounted at the top of a pipe, and estimate distance to the water surface by dividing the return time-of-flight of an emitted high frequency sound wave by the velocity of that wave (Angrisani et al., 2009). A shortcoming of ultrasonic sensors is that they require a minimum distance between the sensor and water surface (known as a dead zone or blanking distance) above which the sensor is not able to take measurements (Table 1), constraining the number of potential installation sites. The US instruments tested in the laboratory were the Massa M-300/95 (relabeled as the Telog UT-33u/95) and Global Water WL705, known henceforth as the Massa and GW respectively. These sensors are similar in make, with the primary difference being that the GW includes a data logger that contains the battery power source, while the Massa must be connected to a separate logger for data collection and power.

Sensors that use pressure transducers (PTs) estimate depth using a submerged piezo-resistive chip that is exposed to water pressure and open to the atmosphere through a hose in the communication cable, such that the electrical signal from the chip can be calibrated to water depth. Depending on the sensor design, these electrical signals are processed within the device, or relayed

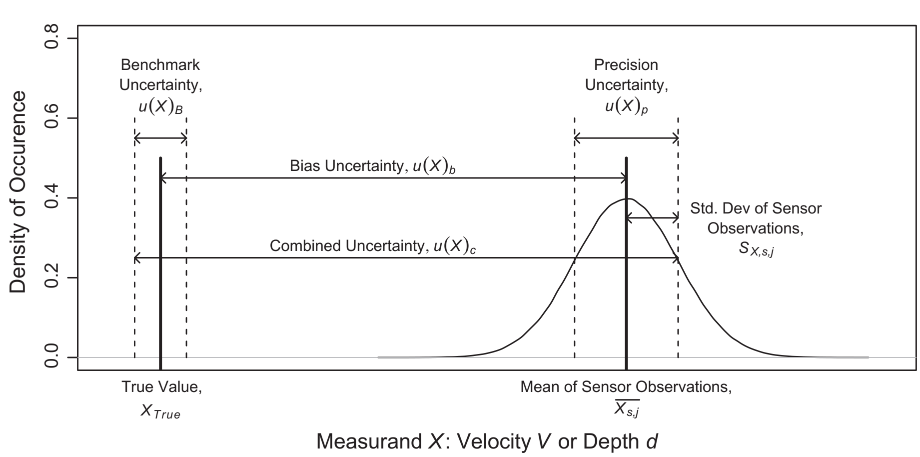

Fig. 1. Uncertainty associated with the observation of a measurand X, adapted from Coleman and Steele (1995).